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The Optical Gravitational Lensing Experiment. The OGLE-III Catalog of Variable Stars. XIV. Classical and Type II Cepheids in the Galactic Bulge*

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ABSTRACT

The fourteenth part of the OGLE-III Catalog of Variable Stars (OIII-CVS) contains Cepheid variables detected in the OGLE-II and OGLE-III fields toward the Galactic bulge. The catalog is divided into two main categories: 32 classical Cepheids (21 single-mode fundamental-mode F, four first-overtone 1O, two double-mode F/1O, three double-mode 1O/2O and two triple-mode 1O/2O/3O pulsators) and 335 type II Cepheids (156 BL Her, 128 W Vir and 51 RV Tau stars). Six of the type II Cepheids likely belong to the Sagittarius Dwarf Spheroidal Galaxy. The catalog data include the time-series photometry collected in the course of the OGLE survey, observational parameters of the stars, finding charts, and cross-identifications with the General Catalogue of Variable Stars.

We discuss some statistical properties of the sample and compare it with the OGLE catalogs of Cepheids in the Large and Small Magellanic Clouds. Multi-mode classical Cepheids in the Galactic bulge show systematically smaller period ratios than their counterparts in the Magellanic Clouds. BL Her in the Galactic bulge stars seem to be brighter than the linear extension of the period–luminosity relations defined by the longer-period type II Cepheids. We also show individual stars of particular interest, like two BL Her stars with period doubling.

Key words: *Stars: variables: Cepheids – Stars: oscillations (including pulsations) – Stars: Population II – Galaxy: center*

*Based on observations obtained with the 1.3-m Warsaw telescope at the Las Campanas Observatory of the Carnegie Institution for Science.

1. Introduction

The OGLE-III Catalog of Variable Stars (OIII-CVS) is a continuously growing collection of variable stars detected in the fields observed in the course of the third phase of the Optical Gravitational Lensing Experiment. The parts of the catalog published so far contain in total 193 000 variable stars of various types identified in the Large (LMC) and Small Magellanic Clouds (SMC) and in the Galactic bulge. Among others, we published the catalogs of Cepheids in the LMC (Soszyński *et al.* 2008ab) and SMC (Soszyński *et al.* 2010ab), and recently we released the catalog of 16 836 RR Lyr stars in the Galactic center (Soszyński *et al.* 2011). This paper presents the sample of classical and type II Cepheids detected in the 68.7 square degrees toward the Galactic bulge.

The first Cepheids in the direction of the Galactic center (but located much closer, in the foreground of the bulge) were discovered in the nineteenth century (Schmidt 1866, Sawyer 1886, Roberts 1894). The first Cepheids that belong to the bulge were discovered by A. J. Cannon during the survey for variable stars carried out by the Harvard College Observatory (Pickering 1908, 1911). In subsequent decades, the effort of many observers (*e.g.,* Swope 1940, Hertzsprung 1941, Plaut 1948, 1958, 1971, Oosterhoff and Horikx 1952, Oosterhoff *et al.* 1954, Ponsen 1955, Hoffleit 1964, Kooreman 1968) increased to about 150 the number of known classical and type II Cepheids in the region of the Galactic bulge.

Since the late twentieth century the number of known variable stars has grown very fast thanks to the huge amount of photometric data collected by the microlensing surveys. The second phase of the OGLE project (OGLE-II) have yielded the sample of 54 type II Cepheids in the Galactic bulge presented by Kubiak and Udalski (2003). This sample, extended by several Cepheids from the OGLE-III project, was analyzed by Groenewegen *et al.* (2008). From the latest studies, it is worth noting the discovery of three long-period classical Cepheids in the nuclear bulge done in the near-infrared domain by Matsunaga *et al.* (2011b). This discovery affects our understanding of the star formation history in the center of the Milky Way.

The catalog presented here contains both, classical and type II, Cepheids observed toward the Galactic bulge. Classical Cepheids in our sample are generally short-period variables and some of them seem to be located behind the Galactic bulge. Variables of this type in front of the bulge are too bright and saturate in the OGLE images. Most of our type II Cepheids belong to the Galactic bulge, which results in a distinct period–luminosity (PL) relation followed by these stars. Several Cepheids in our catalog likely belong to the Sagittarius Dwarf Spheroidal Galaxy (Sgr dSph).

The paper is structured as follows. In Section 2 we present the photometric data and the reduction methods. Section 3 describes the selection and classification of the Cepheids. In Section 4 we present the catalog itself and compare our sample with the set of variables included in the General Catalogue of Variable Stars (GCVS) and other sources. In Section 5 we discuss our results.

2. Observational Data

The catalog was compiled from the observations taken between 1997 and 2009 by the second and third stages of the OGLE survey. Both stages were carried out with the 1.3-m Warsaw telescope at the Las Campanas Observatory, Chile. The observatory is operated by the Carnegie Institution for Science. During the OGLE-II project (1997–2000) the Warsaw telescope was equipped with the "first generation" camera with a SITe 2048×2048 CCD detector working in drift-scan mode. In 2001 this camera was replaced by the eight chip mosaic CCD camera (Udalski 2003a) covering approximately 35×35 arcmin^2 in the sky with the scale of 0.26 arcsec/pixel.

Time-series photometry was obtained with the *I* and *V* filters, closely resembling the standard system. The number of observations significantly varies from field to field: from several dozen to about 3000 measurements in the *I*-band, and up to 50 points in the *V*-band. Similarly to the catalog of RR Lyr stars (Soszyński *et al.* 2011) we restricted our search only to the fields with at least 30 *I*-band observations, which gave the sky coverage of 68.7 square degrees.

The OGLE data reduction pipeline is based on the Difference Image Analysis (DIA) method developed by Alard and Lupton (1998) and Woźniak (2000). For 18 bright Cepheids, which saturate in the DIA reference images, we provide the DoPhot *I*-band photometry (Schechter *et al.* 1993). These stars are flagged in the remarks of the catalog. Instrumental magnitudes were transformed to the standard system using the procedure introduced by Udalski *et al.* (2008). Following the recipe of Szymański *et al.* (2011) we also applied a small correction to the *I*-band measurements for stars redder than $(V-I) = 1.5$ mag.

Since many Cepheids in our catalog have a limited number of observations in the *V*-band, we used the following method to derive the $(V-I)$ color indices for these objects. For a given star we used its well sampled *I*-band light curve as a template light curve which was fitted to the *V*-band observations. For each such a template light curve we adjusted the mean magnitude, amplitude and phase shift between *I*- and *V*-bands. Then using our transformed template light curve we derived intensity mean magnitude in the *V*-band.

The magnitudes of Cepheids were dereddened using the extinction maps obtained by Pietrukowicz *et al.* (2011) on the basis of the OGLE-III catalog of RR Lyr stars (Soszyński *et al.* 2011). Following Pietrukowicz *et al.* (2011) we adopted an anomalous extinction law, $R_I = A_I/E(V-I) = 1.08$, in agreement with the earlier investigation of Udalski (2003b).

3. Selection and Classification of Cepheids

The selection of Cepheids toward the Galactic bulge was performed using generally the same methods as for RR Lyr stars (Soszyński *et al.* 2011). We searched the database of over 3×10^8 stars observed by the OGLE project around the Milky

Way center. For each star we found the most significant periods using the FNPEAKS code kindly provided by Z. Kołaczkowski. The *I*-band light curves with the primary periods between 1 and 50 days and amplitudes above 0.1 mag were inspected by eye and initially divided into pulsating, eclipsing and other variable stars.

Most of the "other" variables turned out to be spotted stars with characteristic changes of amplitude, mean luminosity and light curve shape. The light curves of some of these objects are very similar to the pulsating stars (especially when the OGLE observations covered only two or three seasons) and were initially categorized as Cepheids. However, upon further analysis we investigated the OGLE-IV light curves of our candidates for pulsating stars and we filtered out the spotted variables from our catalog. The final pulsation periods given in this catalog were derived with the TATRY code (Schwarzenberg-Czerny 1996). Each Cepheid was also searched for secondary periods by prewhitening the light curves with the primary periods and deriving periodicities for residual data.

Our final classification of variable stars was based primarily on their light curve morphology, but we also took into account their positions in the PL and color–magnitude diagrams, ratio of amplitudes in the *I*- and *V*-bands, period ratios (for multiperiodic stars), etc. Our final list of Cepheids toward the Galactic bulge contains 367 objects.

3.1. Classical Cepheids

When Baade (1952) announced his revision of the extragalactic distance scale, it became clear that classical (or type I) and type II Cepheids constitute separate classes of variable stars. Our catalog contains 32 classical Cepheids, of which 11 stars have the dominant pulsation periods below 1 day and were identified by us earlier, during the search for RR Lyr stars in the Galactic bulge (Soszyński *et al.* 2011). Actually, several of these short-period Cepheids were included in the catalog of RR Lyr stars, usually with a remark "possible Cepheid". We provide their cross-identifications in the remarks of the catalog.

The OGLE-III catalogs of pulsating stars in the LMC (Soszyński *et al.* 2008a, Poleski *et al.* 2010) revealed that the first-overtone classical Cepheids and δ Sct stars follow the same, continuous PL relation, while the fundamental-mode pulsators are naturally divided by the lack of stars with periods between approximately 0.4 and 1 day. Thus, the boundary period between the overtone Cepheids and δ Sct stars may be freely adopted, and we used a similar borderline like in the Magellanic Clouds. The shortest first-overtone period in our catalog is 0.23 days. The fundamental-mode Cepheids toward the bulge have periods longer than 0.97 days, with the exception of a double-mode object OGLE-BLG-CEP-21 with the fundamental-mode period of about 0.78 days. In the OGLE database we also detected double- and triple-mode pulsators with the fundamental-mode periods of about 0.4 days. We classified these objects as δ Sct stars and we will include them in the next parts of our Catalog.

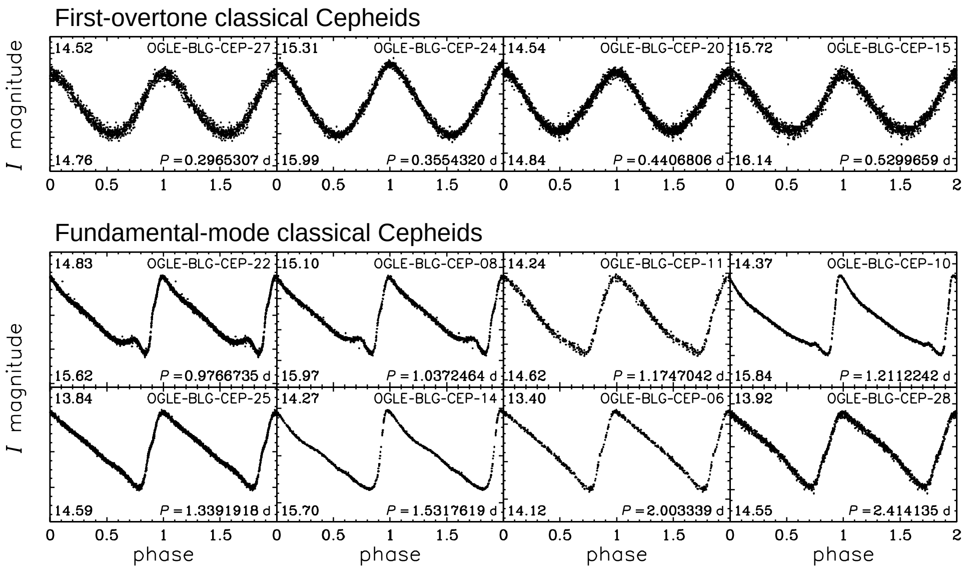

Fig. 1. Sample light curves of single-mode classical Cepheids in the Galactic bulge. *Upper panels* show first-overtone stars, while *lower panels* present fundamental-mode Cepheids brighter than the PL relation for type II Cepheids (see discussion in Section 5). Note that the range of magnitudes varies from panel to panel. Numbers in the left corners show the minimum and maximum magnitudes of the range.

Four short-period classical Cepheids in our sample are single-mode overtone pulsators. The light curves of these stars are shown in Fig. 1. We also found two double-mode Cepheids pulsating simultaneously in the fundamental mode and the first overtone, three pulsators with the first and second overtones excited and two triple-mode Cepheids with the first three overtones excited. The remaining 21 classical Cepheids are fundamental-mode pulsators, which were distinguished from the type II Cepheids on the basis of their light curve shapes.

3.2. Type II Cepheids

Type II Cepheids (sometimes called Population II Cepheids) are low-mass pulsating stars of the thick disk and halo populations. They are divided into three subtypes – BL Her, W Vir, and RV Tau stars – which are associated with consecutive phases of stellar evolution after exhaustion of helium in the core (Schwarzschild and Härm 1970, Strom *et al.* 1970, Gingold 1974, 1976). BL Her stars are post-horizontal branch stars evolving towards the asymptotic giant branch. W Vir stars are thought to undergo blueward loops from the asymptotic giant branch due to helium shell flashes. RV Tau stars cross the instability strip evolving away from the asymptotic giant branch toward the white dwarf domain.

Our catalog contains 335 type II Cepheids. Fig. 2 presents an example set of light curves from the sample. As in the catalogs in the LMC and SMC (Soszyński *et al.* 2008b, 2010b), the transition between BL Her and RR Lyr stars was defined at

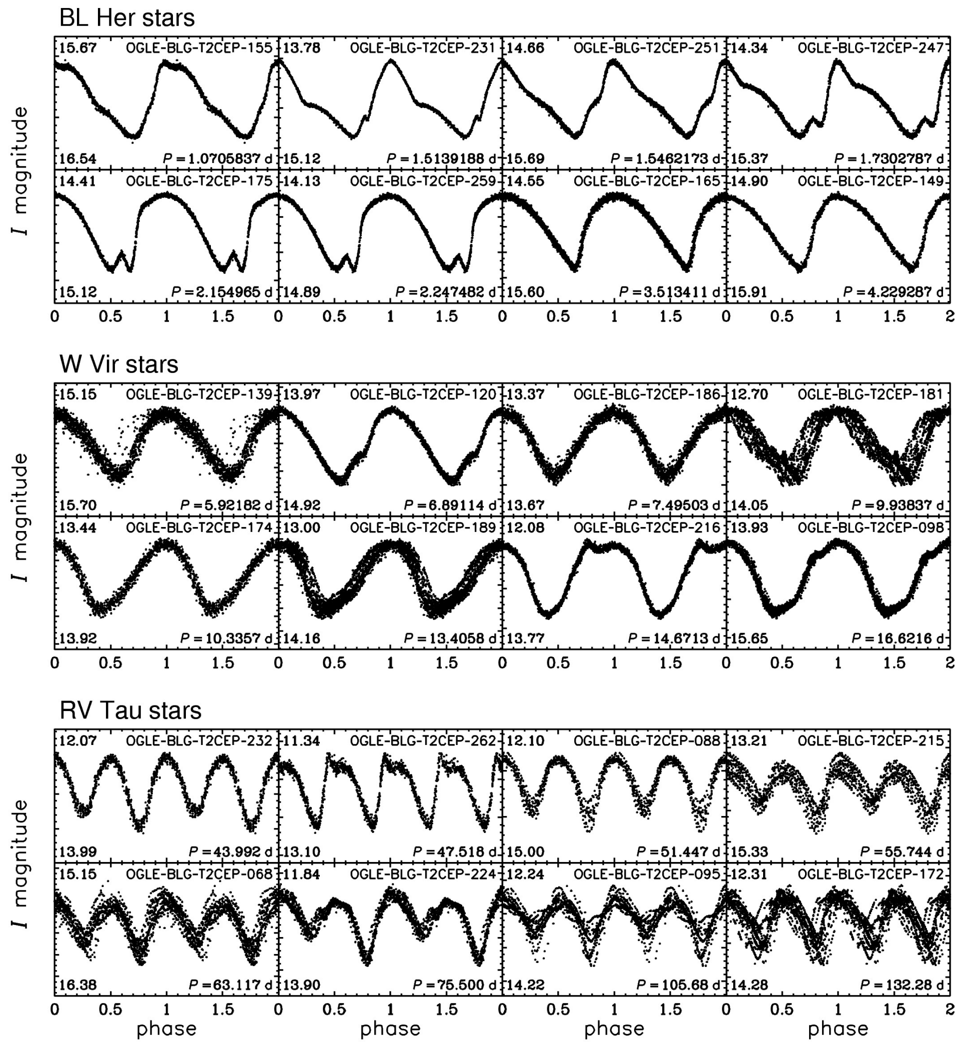

Fig. 2. Sample *I*-band light curves of type II Cepheids in the Galactic bulge. *Upper panels* show BL Her stars, *middle panels* – W Vir stars, and *lower panels* – RV Tau stars (folded with the "double" periods). Note that the range of magnitudes varies from panel to panel. Numbers in the left corners show the minimum and maximum magnitudes of the range.

$P = 1$ day. However, the parameters of the Fourier decomposition of light curves suggest that the two classes overlap in period space and the distinction between them is not a clear-cut. Fig. 3 shows the Fourier coefficient ϕ_{21} (Simon and Lee 1981) plotted against the logarithm of the period for RRab stars (from the catalog of Soszyński *et al.* 2011) and short-period BL Her stars. The symbols surrounded by circles indicate nine BL Her stars which seem to be an extension of the RR Lyr stars to periods longer than 1 day. Lower panels of Fig. 3 present light curves of three typical RR Lyr stars with periods just below 1 day, and three stars with periods above 1 day, but likely belonging to the same class. These objects may be called

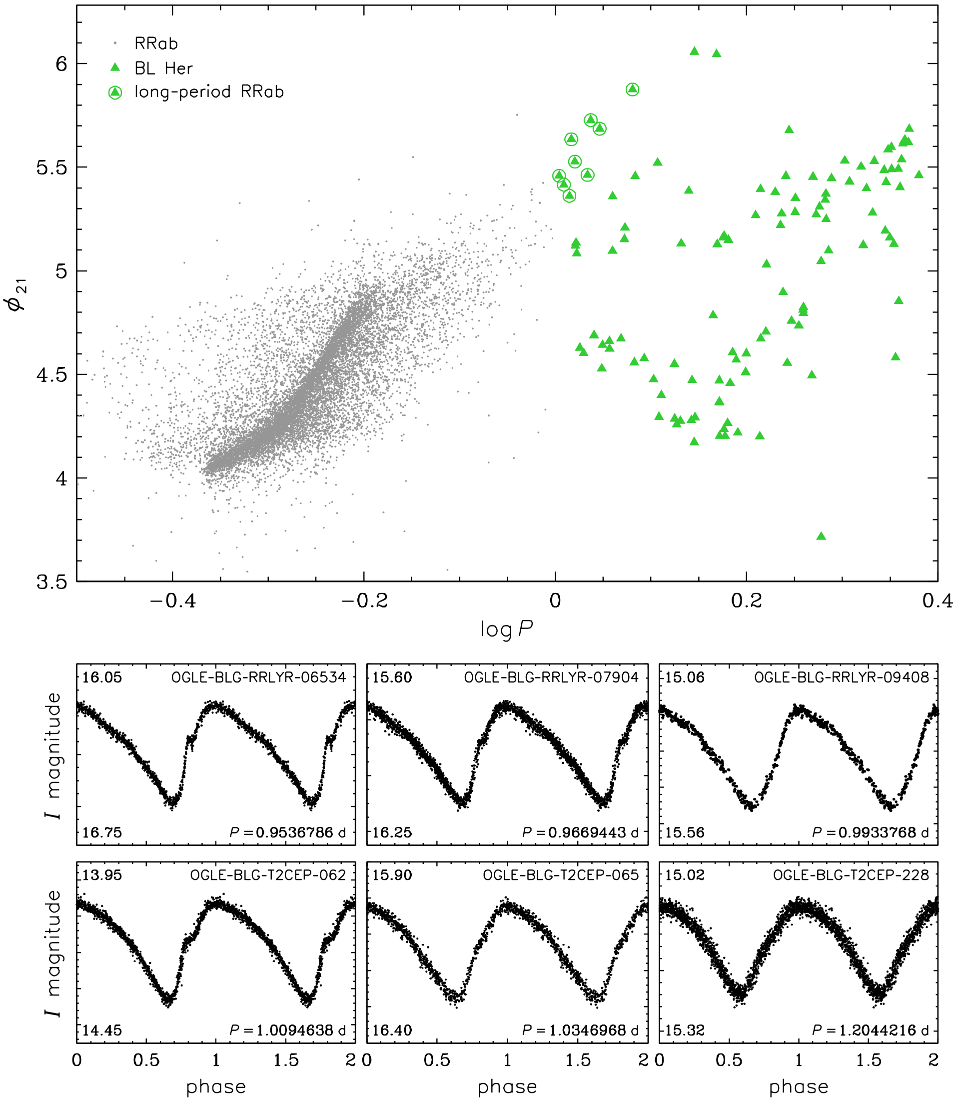

Fig. 3. *Upper panel*: Fourier coefficients ϕ_{21} *vs.* the logarithm of the periods for RRab stars (grey points) and short-period type II Cepheids (green triangles). Candidates for RR Lyr stars with periods above 1 day are surrounded by circles. *Lower panels*: Light curves of three RR Lyr stars with periods just below 1 day, and three candidates for long-period RR Lyr stars.

long-period RR Lyr stars, which moves the upper limit of the RR Lyr periods to over 1.2 days. However, as we mentioned, in this catalog all Population II pulsators with periods longer than 1 day are called BL Her stars.

On the other hand, one can expect that period of 1 day is not the shortest period of the genuine BL Her stars and some type II Cepheids may have been included in our catalog of RR Lyr stars in the bulge (Soszyński *et al.* 2011). The light curves of the genuine BL Her stars are shown in Fig. 2. Their Fourier coefficient ϕ_{21}

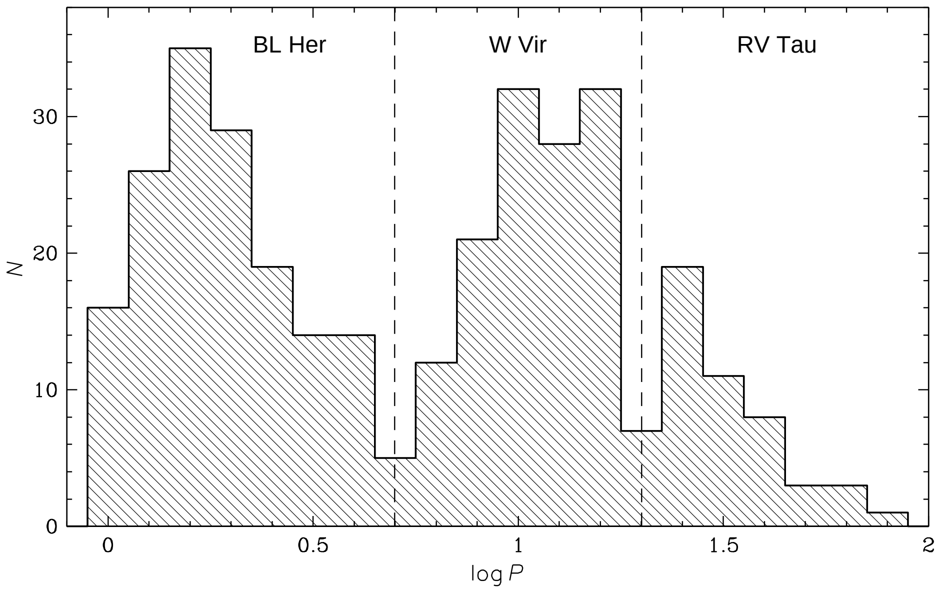

Fig. 4. Period distribution of type II Cepheids in the Galactic bulge. Vertical dashed lines show the thresholds, 5 d and 20 d, used to divide BL Her, W Vir and RV Tau stars.

is below 4.7 for periods of about 1 day. The stars with similar periods and with $4.7 < \phi_{21} < 5.3$, *i.e.,* located between genuine BL Her and long-period RR Lyr stars, may be included to both groups. It is noteworthy that in the Magellanic Clouds we did not notice such a distinct group of long-period RR Lyr stars. An attempt to separate long-period RR Lyr stars from the short-period BL Her stars based on their light curves was undertaken by Diethelm (1983).

As a borderline between BL Her and W Vir stars we adopted a period of 5 days, *i.e.,* longer than in the Magellanic Clouds (4 days). In the bulge this value seems to best separate both classes of type II Cepheids. First, the period distribution (Fig. 4) shows a local minimum for $P \approx 5$ days. Second, type II Cepheids with periods below 5 days are on average bluer than Cepheids with longer periods, which is visible in the color–magnitude diagram (Fig. 5). Such a discontinuity in $(V-I)$ colors between BL Her and V Wir stars was also found in the Magellanic Clouds. Third, type II Cepheids with periods above and below 5 days seem to obey different PL relations. We will return to this point in the discussion.

The boundary between W Vir and RV Tau stars was traditionally adopted at $P =$ 20 days ("single" period, *i.e.,* the interval between successive minima). The only exception is OGLE-BLG-T2CEP-045 with a single period of 19.36 days, which displays clear alternations of deep and shallow minima, *i.e.,* the typical behavior of RV Tau stars. Not all long-period type II Cepheids ($P > 20$ days) show clear alternations of cycles, however all these stars are called RV Tau stars in our catalog.

In the Magellanic Clouds (Soszyński *et al.* 2008b, 2010b) we distinguished an additional subclass of type II Cepheids, which we called peculiar W Vir stars.

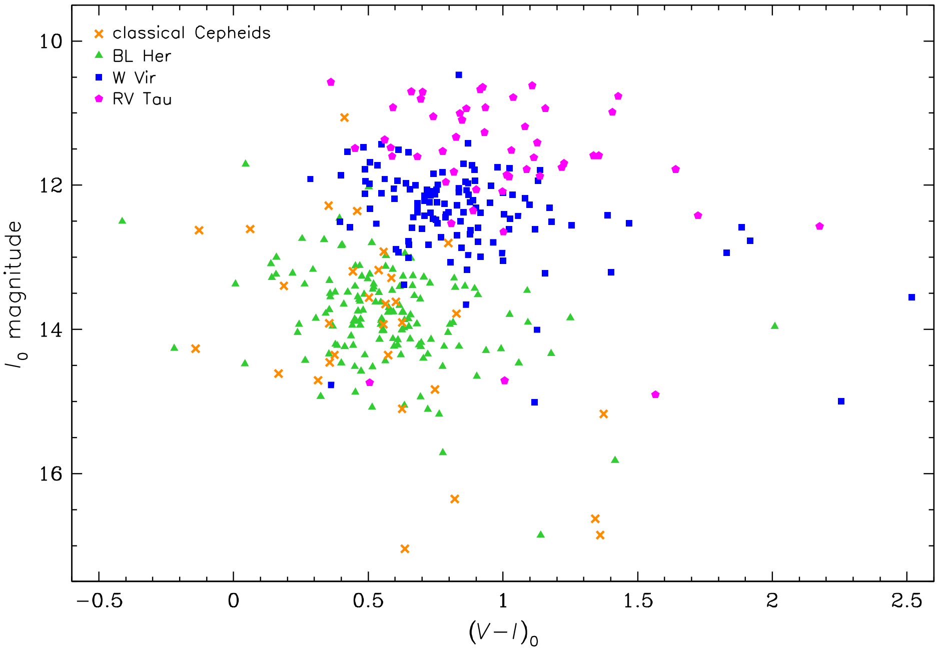

Fig. 5. Color–magnitude diagram for classical (yellow crosses) and type II (green, blue and magenta symbols) Cepheids toward the Galactic bulge. The color indices and luminosities were dereddened using the extinction maps by Pietrukowicz *et al.* (2011).

These Cepheids are characterized by higher luminosities, on average bluer colors and a different light curve morphology than regular W Vir stars. Large fraction of peculiar W Vir stars show eclipsing or ellipsoidal modulation superimposed on the pulsation light curves, which suggests that all these stars are members of binary systems. Candidates for peculiar W Vir stars were also found in the Milky Way (Matsunaga *et al.* 2009, Welch and Foster 2011).

In the Galactic bulge we identified no evident peculiar W Vir star. Although a lot of type II Cepheids have Fourier coefficients similar to the peculiar W Vir stars, these objects do not satisfy other conditions: they are not brighter and bluer than regular W Vir stars. We also did not detect any Cepheid with signs of binarity. Thus, in this catalog we did not divided W Vir stars into “regular” and “peculiar” variables.

4. Catalog of Cepheids Toward the Galactic Bulge

The OGLE-III catalog of classical Cepheids toward the Galactic bulge comprises 32 objects, of which 21 pulsate solely in the fundamental mode (F), four are single-mode first-overtone pulsators (1O), two stars are F/1O double-mode Cepheids, three – 1O/2O double-mode Cepheids, and two – 1O/2O/3O triple-mode Cepheids. The sample of 335 type II Cepheids has been divided into 156 BL Her, 128 W Vir, and 51 RV Tau stars. Six type II Cepheids likely belong to Sgr dSph.

The catalogs are accessible through the anonymous FTP site or *via* the web interface:

ftp://ftp.astrouw.edu.pl/ogle/ogle3/OIII-CVS/blg/cep/
ftp://ftp.astrouw.edu.pl/ogle/ogle3/OIII-CVS/blg/t2cep/
http://ogle.astrouw.edu.pl

The FTP sites are organized as follows. The lists of Cepheids with their J2000 equatorial coordinates, classification, identifications in the OGLE-II and OGLE-III databases and in the GCVS are given in the ident.dat files. The stars are arranged in order of increasing right ascension and designated OGLE-BLG-CEP-NN or OGLE-BLG-T2CEP-NNN for classical and type II Cepheids, respectively. The observational parameters of the Cepheids – intensity-averaged $\langle I\rangle$ and $\langle V\rangle$ magnitudes, periods with uncertainties (derived with the TATRY code by Schwarzenberg-Czerny 1996), peak-to-peak *I*-band amplitudes and parameters of the Fourier light curve decomposition R_{21}, ϕ_{21}, R_{31}, ϕ_{31} (Simon and Lee 1981) – are given in separate files. Additional information on some objects can be found in the files remarks.txt. The OGLE-II and OGLE-III multi-epoch *VI* photometry can be downloaded from the directory phot/. Finding charts for each star are stored in the directory fcharts/. These are $60'' \times 60''$ subframes of the *I*-band DIA reference images.

The completeness of the catalog was judged by comparing our sample with the list of type II Cepheids found by Kubiak and Udalski (2003) and with the GCVS (Samus *et al.* 2011). The cross-identification with the OGLE-II catalog of Kubiak and Udalski (2003) revealed 12 missing objects in our sample, of which eight stars have periods below 1 day and were included in the OGLE-III catalog of RR Lyr stars (Soszyński *et al.* 2011). The remaining four missing stars turned out to be reclassified in the OGLE-III database as eclipsing or spotted variables.

We cross-matched our catalog with the stars classified as CEP, DCEP, CW, CWA, CWB, RV, RVA or RVB in the GCVS. From 49 such objects, that can be potentially found in the OGLE-II and OGLE-III fields in the Galactic bulge, we unambiguously identified 24 Cepheids. Most of the remaining objects turned out to be much too bright to be present in the OGLE database. Some variables classified in the GCVS as RV Tau stars have light curves indistinguishable from the long-period variables (SRV). These objects also have not been included in our catalog. From the six type II Cepheids discovered with the Hubble Space Telescope by Pritzl *et al.* (2003) in the core of the globular cluster NGC 6441 we detected only one object (V6 = OGLE-BLG-T2CEP-083) – the most distant one from the center of the cluster.

It seems that the OGLE-III catalog of Cepheids in the Galactic bulge is nearly complete for stars with the *I*-band magnitudes in the range 12–20 mag, but there are brighter and probably fainter Cepheids which are not included in our sample. Also, our catalog is incomplete in the cores of dense globular clusters.

Fig. 6 shows the position of classical and type II Cepheids in the sky. One can notice different spatial distributions of both types of Cepheids. Old stars are strongly concentrated toward the Galactic center, like RR Lyr stars (Soszyński *et al.*

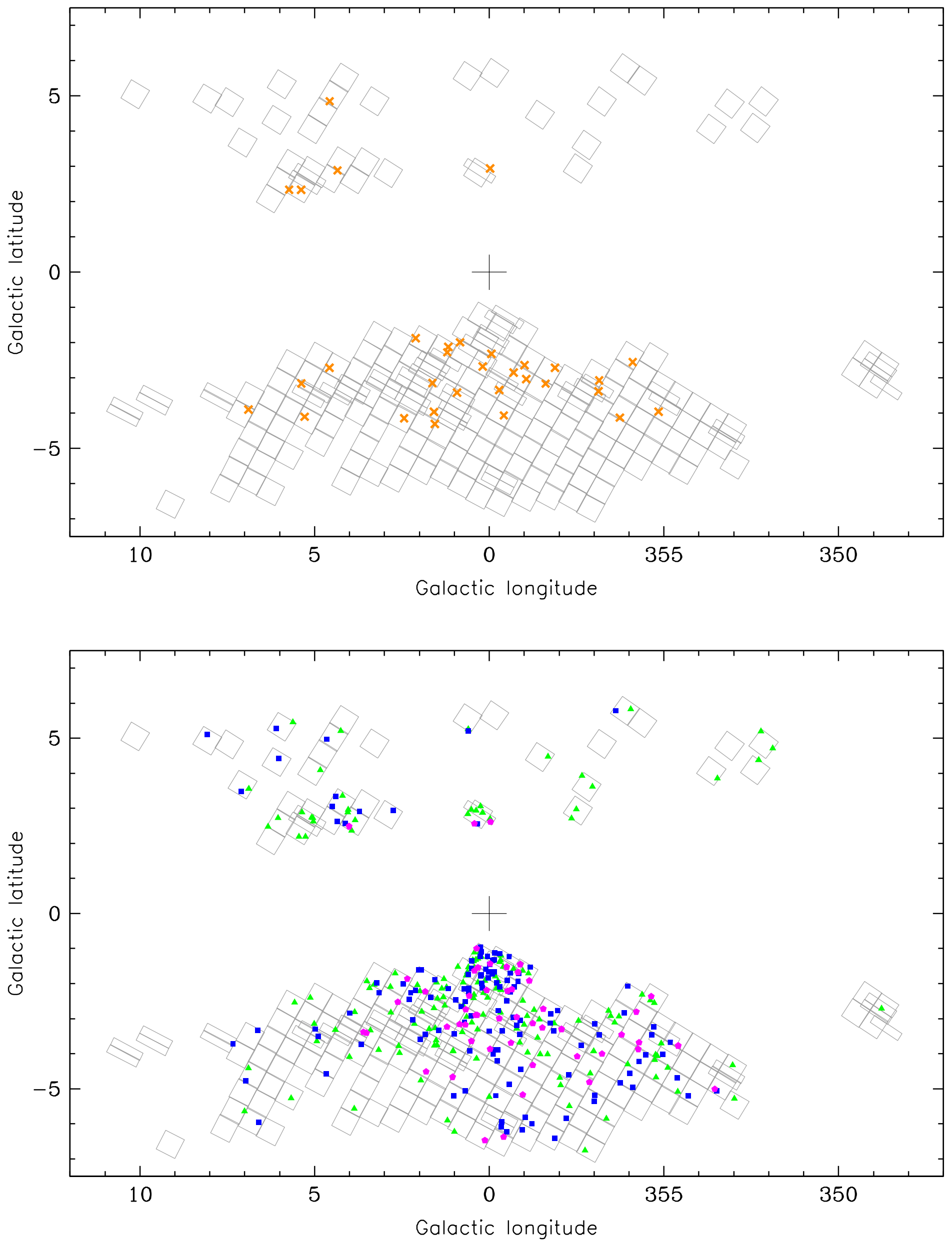

Fig. 6. Spatial distribution of classical (*upper panel*) and type II (*lower panel*) Cepheids toward the Galactic bulge. Different symbols correspond to types of stars as shown in Fig. 5. Grey contours show the OGLE-II and OGLE-III fields with the number of observations exceeding 30.

2011). Classical Cepheids are distributed almost parallel to the Galactic plane, between Galactic latitudes $-5^\circ < b < 5^\circ$. The OGLE-III fields closest to the Galactic center (with the largest interstellar extinction) are completely omitted by the classical Cepheids.

5. Discussion

5.1. Classical Cepheids

It has been known for a long time that in the Galactic bulge type II Cepheids dominate over classical Cepheids (Oosterhoff 1956). Indeed, our catalog contains an order of magnitude larger sample of type II Cepheids than classical Cepheids. Moreover, the reddening-free PL diagram shown in Fig. 7 raises doubts whether the observed classical Cepheids belong to the bulge.

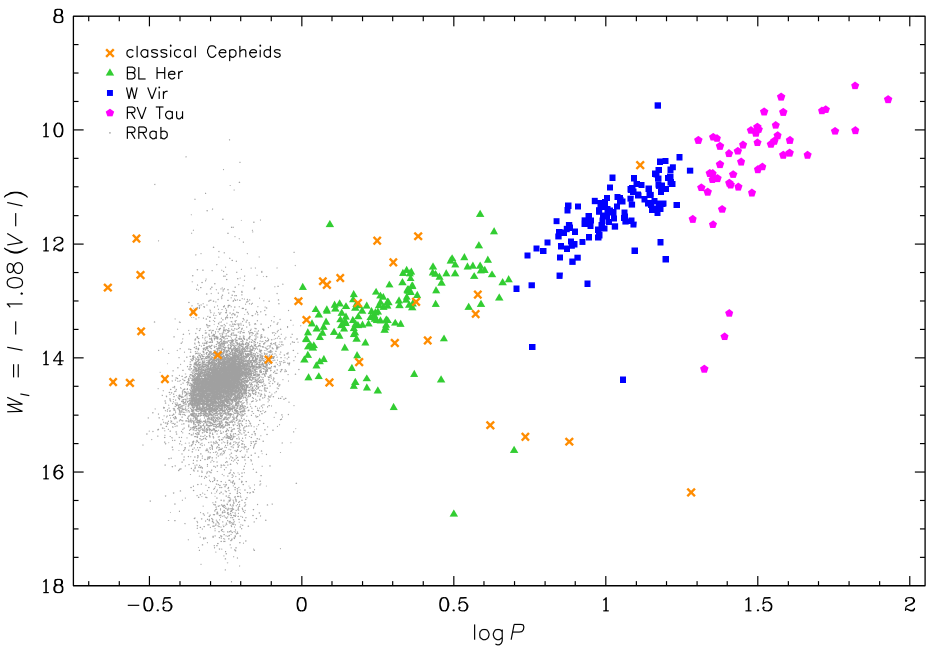

Fig. 7. Period–W_I diagram for classical Cepheids (yellow crosses), type II Cepheids (green, blue and magenta symbols) and RR Lyr stars (grey points) toward the Galactic bulge. W_I is the reddening-free Wesenheit index, defined as $W_I = I - 1.08(V - I)$.

While type II Cepheids concentrate along a well-defined PL relation, classical Cepheids do not follow a distinct PL sequence. In the LMC (Soszyński *et al.* 2008b) fundamental-mode type I Cepheids are by about 1.3 mag brighter than type II Cepheids for periods around 1 day, and 2.5 mag brighter for periods above 20 days. In the bulge we have a group of short-period (0.98–2.41 days) fundamental-mode classical Cepheids by only 0.7 mag brighter than BL Her stars. The light curves of these variables are shown in Fig. 1.

There are three possible explanations of this inconsistency between the Galactic bulge and LMC.

1. All fundamental-mode classical Cepheids in our sample are located in the Galactic disk behind the bulge, and therefore they have lower apparent luminosities compared to type II Cepheids. This hypothesis is supported by

the spatial distribution of classical Cepheids (Fig. 6), which is completely different than for type II Cepheids and other members of the bulge (RR Lyr stars, red clump stars). On the other hand, most of the classical Cepheids in our catalog have colors typical for Cepheids in the bulge (Fig. 5) and are not additionally reddened by the interstellar matter behind the bulge. This argument supports the following two hypotheses.

2. The Cepheids above the type II Cepheids PL relation belong to the bulge, but have lower absolute luminosities than classical Cepheids. These objects may be so called anomalous Cepheids – brighter than type II and fainter than classical Cepheids. We found 62 fundamental-mode anomalous Cepheids in the LMC (Soszyński *et al.* 2008b) and only three candidates for such stars in the SMC (Soszyński *et al.* 2010a).

3. The Cepheids from the mentioned group are normal classical Cepheids belonging to the bulge, but the BL Her stars in the bulge are systematically brighter than the same stars in the LMC. Indeed, in Fig. 7 BL Her stars seem to lie above the linear extension of the PL relation defined by the longer-period type II Cepheids. In the SMC BL Her stars are also placed above the PL relation fitted to the W Vir stars (Matsunaga 2011a).

If the latter possibility occurs, the classical Cepheids in the Galactic bulge have short periods, below 2.5 days. It is in agreement with Matsunaga *et al.* (2011b), who discovered three Cepheids with periods of approximately 20 days, and no Cepheids with shorter periods. However, due to the detection limits in the near-infrared bands, their survey was sensitive only to the Cepheids with periods longer than 5 days. Regardless of which hypothesis is true, there is no doubt that our catalog contains also classical Cepheids located behind the bulge. They are much fainter and redder (due to the additional extinction) than typical Cepheids in the bulge.

The OGLE-III catalog of classical Cepheids toward the Galactic bulge comprises an exceptionally large fraction (22% of the total sample) of multi-mode pulsators. In the LMC and SMC we observed 8% and 6% of multi-mode Cepheids, respectively. The observational parameters of the two triple-mode Cepheids in the bulge are given in Table 1. Fig. 8 shows their light curves folded with the three pulsation periods, each one after prewhitening with the other two modes.

The Petersen diagram (shorter-to-longer period ratio *vs.* the logarithm of the longer period) is shown in Fig. 9. We also plotted here double- and triple-mode Cepheids from the Magellanic Clouds (Soszyński *et al.* 2008a, 2010a) and δ Sct stars from the LMC (Poleski *et al.* 2010). The diagram reveals another remarkable property of multi-mode Cepheids in the bulge: the ratio of the second-overtone to first-overtone periods is distinctly lower than in the Magellanic Clouds. Similar feature concerns the period ratios of the third and first overtones, and third and second overtones in triple-mode Cepheids.

Table 1

Triple-mode Cepheids in the Galactic bulge

Star name	$\langle I\rangle$ [mag]	$\langle V\rangle$ [mag]	P_{1O} [days]	A_I^{1O} [mag]	P_{2O} [days]	A_I^{2O} [mag]	P_{3O} [days]	A_I^{3O} [mag]
OGLE-BLG-CEP-16	13.994	15.338	0.2954573	0.147	0.2339744	0.014	0.1950696	0.015
OGLE-BLG-CEP-30	14.184	15.499	0.2303703	0.111	0.1829840	0.027	0.1521731	0.034

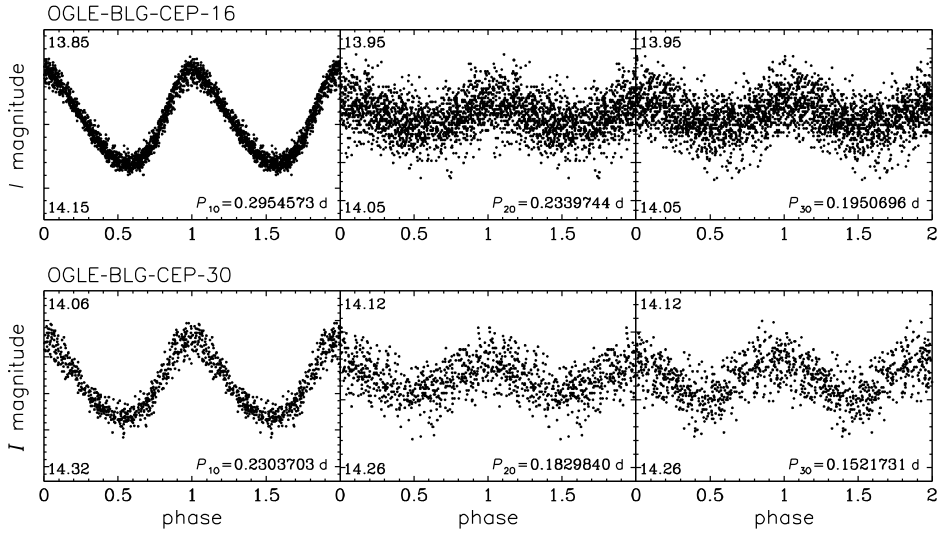

Fig. 8. *I*-band light curves of triple-mode Cepheids in the Galactic bulge. Each mode is shown after prewhitening with the other two modes. Note that the range of magnitudes varies from panel to panel. Numbers in the left corners show the minimum and maximum magnitudes of the range.

5.2. Type II Cepheids

The PL diagram (Fig. 7) shows that most of type II Cepheids in our sample are placed in the Galactic bulge. The scatter of the relation can be largely explained by the depth of the bulge along the line of sight. Six type II Cepheids (two BL Her, one W Vir and three RV Tau stars) are by about 3 mag fainter than type II Cepheids of the same periods in the bulge, and these are probably members of the Sgr dSph, like RR Lyr stars also visible in the lower part of the PL diagram.

Comparison to the PL relations followed by type II Cepheids in the LMC (Soszyński *et al.* 2008b) reveals significant differences. In the LMC RV Tau stars are systematically brighter than the PL relation fitted to BL Her and W Vir stars, while in the bulge such a behavior is not detectable. On the other hand in the LMC (Soszyński *et al.* 2008b) the PL relations of BL Her and W Vir stars were co-linear within the uncertainties while in the bulge BL Her stars are distinctly brighter than the PL relation defined by W Vir stars. This feature is similar to that observed for type II Cepheids in the SMC (Matsunaga *et al.* 2011a). It is worth noting that

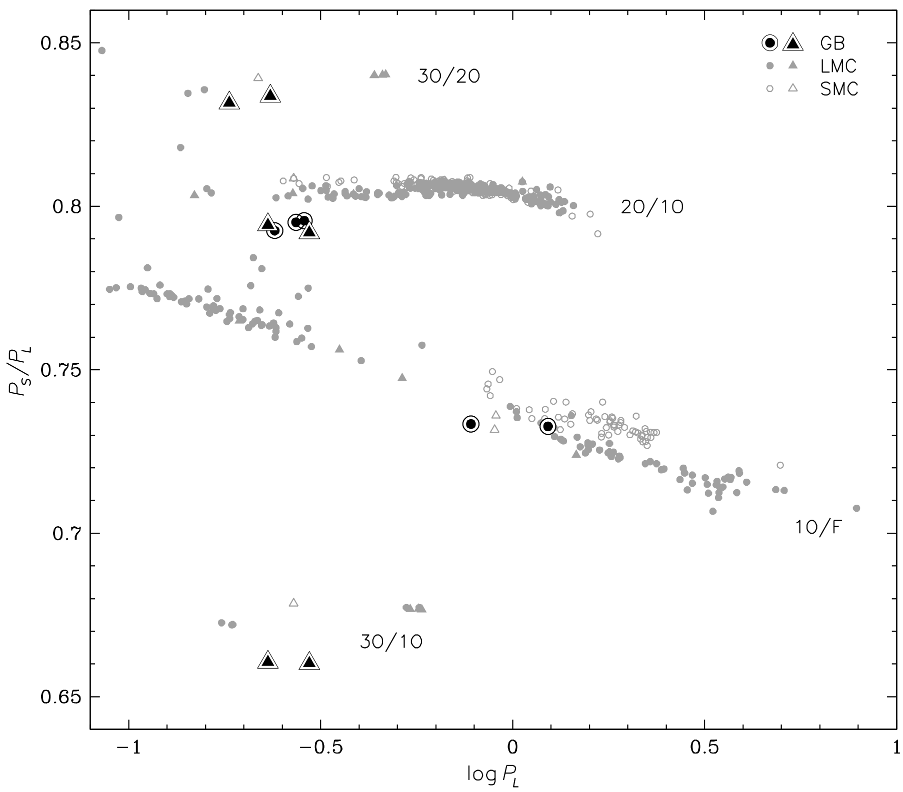

Fig. 9. Petersen diagram for multiperiodic Cepheids in the Galactic bulge (black symbols), LMC (grey solid symbols), and SMC (grey empty symbols). Circles represent double-mode Cepheids (one point per star), while triangles show the period ratios in triple-mode Cepheids (three points per star).

RRab stars, also plotted in Fig. 7, seem to be on the extension of the PL relation for BL Her stars. So, brighter BL Her stars imply brighter RR Lyr stars in the Galactic bulge.

Fig. 2 presents examples of light curves of BL Her, W Vir, and RV Tau stars from our catalog. W Vir stars have on average more scattered light curves than BL Her stars due to variations of period, phase and sometimes amplitude. However, it seems that type II Cepheids in the Galactic bulge have more stable light curves than their counterparts in the Magellanic Clouds. There are also exceptions to this rule, such as a W Vir star OGLE-BLG-T2CEP-059, with so rapid period changes that its OGLE light curve cannot be phased using a constant period.

Our sample of type II Cepheids contains objects of particular interest. We discovered first two cases of BL Her stars with the period doubling (OGLE-BLG-T2CEP-257, OGLE-BLG-T2CEP-279), the behavior predicted theoretically by Buchler and Moskalik (1992). An in-depth analysis of OGLE-BLG-T2CEP-279 (BLG184.7 133264) was performed by Smolec *et al.* (2011).

Fig. 10 presents the light curve of OGLE-BLG-T2CEP-177 – an RV Tau star with variable mean magnitude (RVb type). If the changes of the mean brightness

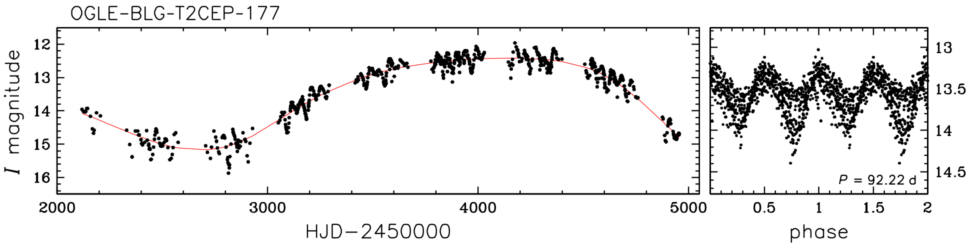

Fig. 10. *I*-band light curve of an RVb star OGLE-BLG-T2CEP-177. *Left panel* shows the unfolded light curve. Red line is the spline function fitted to the light curve. *Right panel* presents the light curve folded with the "double" pulsation periods after subtracting the long-term trend.

are periodic (like in other RVb stars, *e.g.*, OGLE-LMC-T2CEP-200), the eight years of the OGLE-III observations covered only one cycle of these variations. It shows the advantage of the long-term OGLE survey. This objects and other variable stars from this catalog are continuously monitored during the present stage of the OGLE survey – OGLE-IV.

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